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LETTER TO THE EDITOR

Analysis of superconducting Sn/Ti contacts to GaAs/AlGaAs heterostructures by electron focusing

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Abstract. Tin-based superconducting contacts have been successfully made to GaAs/AlGaAs heterostructures in several groups. To identify whether the superconductor contacts directly with the two-dimensional electron gas (2DEG), we study the electronic properties underneath the contact locally by means of an electron focusing technique in a GaAs/AlGaAs device which consists of a Sn/Ti contact and two quantum point contacts. The observation of classical focusing peaks shows the presence of a 2DEG under the contact. Together with inspection by cross-sectional electron microscopy, we conclude that the superconducting contacts are formed not in the 2DEG but somewhere above the 2DEG.

Superconducting contacts made to a high-mobility two-dimensional electron gas (2DEG) in GaAs/AlGaAs heterostructures form one of the interesting subjects in modern condensed matter physics because they may provide ideal systems in which to study experimentally several new phenomena, such as Andreev reflection and the Josephson effect in a quantum point contact (QPC) [1] and supercurrent-carrying bound states [2]. The observation of these effects demands a disorder-free 2DEG and in particular a direct contact between a superconductor (S) and the 2DEG. This means that any normal disordered conducting layers lying between S and the 2DEG will either ruin or weaken the effects.

Recently, superconducting contacts to a GaAs/AlGaAs heterostructure have been produced [3–5]. They are made by evaporating Sn onto the surface and further annealing the sample so that the superconductor can diffuse into the semiconductor (Sm) or can form alloys. Sn is chosen because it can form not only ohmic but also superconducting contacts [6]. To make contacts as homogeneous as possible it is necessary to insert an intermediate thin metal layer, such as a layer of Ti, otherwise droplets of Sn are formed on the surface during annealing, causing poor morphology. Since the 2DEG is embedded 100 nm below the surface, the fabrication method for Si, InAs and InGaAs systems, in which contacts are made by depositing a superconductor directly on a semiconductor, is no longer suitable.

It has been clearly demonstrated that superconducting contacts are formed using this technique since the typical current–voltage (I–V) measurements are characterized by a superconductor gap and superconducting transition around T_c of Sn. However, a crucial question, whether the superconductor diffuses so deep that it forms a direct contact to the 2DEG or whether it contacts electrically with the 2DEG via an intermediate semiconducting layer, remains open.

To provide an answer we have developed a novel type of GaAs/AlGaAs device consisting of a Sn/Ti contact and two QPCs since the measurement of a single superconducting contact cannot resolve the problem. We applied the electron focusing technique [7] for the first time to study the electronic properties underneath a contact. Additionally, we inspected the cross-section of the contact by high-resolution electron microscopy (HREM).

Our starting sample is a MBE-grown GaAs/AlGaAs heterostructure, in which a 2DEG is formed 80 nm below its surface. At $T < 4.2$ K, the sheet electron density n_s is 3.0×10^{11} cm^{-2} and the mobility 1×10^6 cm^2 V^{-1}s^{-1}, giving a mean free path ℓ_e of 10 μm.

The device fabrication starts with patterning AuGeNi contacts and wet etching a Hall bar. Then the native oxide of GaAs is removed in a solution of HCl : $H_2O = 1 : 1$ for 2 min and afterwards the sample is immediately loaded

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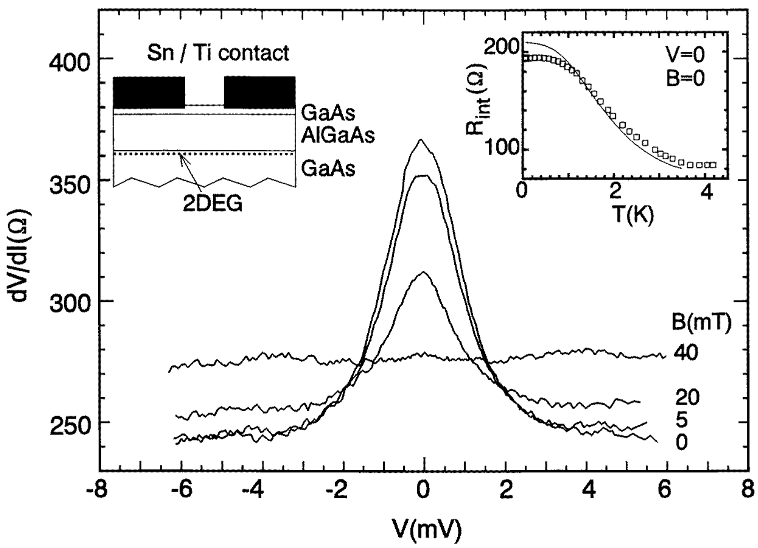

Figure 1. Differential resistance $\mathrm{d}V/\mathrm{d}I$ as a function of dc bias voltage V for a device with two superconducting Sn/Ti contacts connected by a short (4 μm) and wide (16 μm) 2DEG. The measurement is made at T = 80 mK and at magnetic fields from 0 up to 40 mT, which are applied perpendicular to the plane of the 2DEG. The left inset illustrates schematically the cross-section of the device. The right inset shows zero-bias S–Sm interfacial resistance R_{int}, which is the $\mathrm{d}V/\mathrm{d}I$ curve after a series resistance R_{s} of 160 Ω is subtracted, as a function of temperature. Here the points are experimental data and the curve the theoretical result.

into an e-gun evaporation system. As the system pressure reaches 6×10^{-7} Torr, a layer of 10 nm Ti is evaporated in the same way as described in [3] and followed by a layer of 250 nm Sn. These layers are patterned by photolithography and a lift-off technique. To form both the Sn/Ti superconducting and NiAuGe ohmic contacts, annealing takes place on a hot plate at 450 °C in N_2 for 20 s. Roughly speaking, we find that an annealing time between 10 and 30 s can lead to reasonably good ohmic and superconducting contacts. Furthermore, Au/Ti bonding pads and alignment markers needed for accurate location of split gates are fabricated. Finally, the gates for two QPCs are defined using e-beam lithography and aligned to be 0.5 μm away from one of the Sn/Ti boundaries. The separation between the two QPCs is 4.8 μm.

Figure 1 shows the four-terminal differential resistance $\mathrm{d}V/\mathrm{d}I$ of a device without QPCs, but with two Sn/Ti contacts connected by a 2DEG that is 4 μm long and 16 μm wide, as a function of dc voltage V at different magnetic fields. The fields are applied perpendicular to the plane of the 2DEG. This device is prepared under the conditions described and will serve to characterize the S–Sm interfaces. Its cross-section is illustrated schematically in the left inset of figure 1. A peak around $V = 0$ and 'minima' near ±3 mV on the $\mathrm{d}V/\mathrm{d}I$ curve are a signature of superconducting contacts because they can be fully suppressed by increasing B up to 30 mT or increasing T up to 3.8 K. These values are consistent with H_{c} and T_{c} for bulk Sn ($T_{\mathrm{c}} = 3.7$ K, $H_{\mathrm{c}} = 31$ mT and $2\Delta(0) \approx 1.2$ meV). The normal state resistance R_{N} derived for both $T \gg T_{\mathrm{c}}$ and $V \gg 2\Delta/e$ is around 240 Ω. Furthermore, an increase of R_{N} with B is due to the magnetoresistance in the 2DEG.

The dependence of the I–V characteristics on a barrier strength parameter Z has been described in the BTK model [8]. The sample geometry considered in this model is a point-contact S–N (N denotes metal) junction with a delta-function potential for the barrier in between. This geometry is, however, different from ours. In particular, the potential barrier at an annealed contact may have a finite thickness, and may also be laterally inhomogeneous. To estimate Z, we assume that the BTK results also apply to our case. The 'minima' in $\mathrm{d}V/\mathrm{d}I$ at voltages of about 3 times $\pm 2\Delta/e$ suggest that there is a series resistance R_{s} in addition to the S–Sm interfacial resistance R_{int}. The R_{s} is probably contributed by the doped semiconductor–2DEG interfacial resistance. Having subtracted an R_{s} of 160 Ω from $\mathrm{d}V/\mathrm{d}I$ ($V = 0$), we can fit the BTK theoretical expression to our R_{int} versus T data reasonably well. Both the data and the theoretical curve are shown in the right inset of figure 1. From these fits we derive a Z of 1.0, suggesting an Andreev reflection probability of 0.1 at $V = 0$.

The normal-state value of R_{int} is much larger than the Sharvin resistances of the metal–semiconductor interface for $Z = 1.0$. The latter is $\sim 4 \times 10^{-3}$ Ω, estimated by using the transfer length and the carrier density for the doped GaAs and AlGaAs given in [9]. This result, together with large variations in R_{N} among the devices found in the experiment, indicates that the S–Sm interface is not homogeneous and only a very small part of the interface is transparent.

Although the general behaviour described here has been observed in many similar devices, the I–V characteristic varies from one device to another, i.e. at $T = 0.1$ K the ratio $R(V = 0)/R_{\mathrm{N}}$ varies from 1.2 to 3.4, the minima on the $\mathrm{d}V/\mathrm{d}I$ curve from ±1.1 to ±3 mV, and R_{N} between 0.13 and 1 kΩ. Furthermore, some devices show a decrease of $\mathrm{d}V/\mathrm{d}I$ below the Sn gap voltage, being similar to the

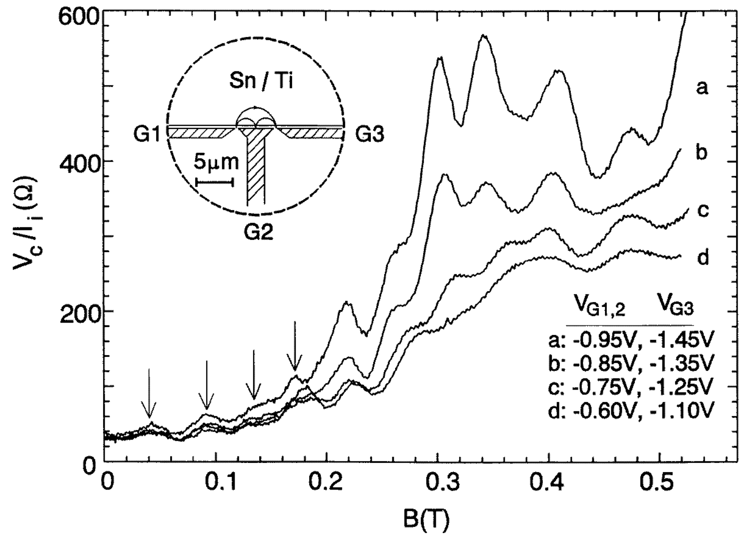

Figure 2. The ratio of collector voltage and injector current V_c/I_i as a function of perpendicular magnetic field at four sets of gate voltages and at T = 7 K. The left inset illustrates the key part of the device. The distance between the gate and the Sn/Ti contact is 0.5 μm, and the two QPCs are 4.8 μm apart.

data in Sn/Pd contacts [4], or an increase in dV/dI but with an extra dip near $V = 0$, or even no signatures of the S–Sm interfaces, although they are very similar.

Now we present our main experimental results obtained from the device with two QPCs in front of a Sn/Ti contact. The key part of the device is illustrated in the left inset of figure 2. To examine the contact we performed a magnetic electron focusing measurement where one QPC injects electrons into the 2DEG and the other QPC collects the electrons. Since they travel from one QPC to another in a half circle with a cyclotron radius r_{cycl}, being 2.4 μm for the first focusing peak, we can verify whether there exists a 2DEG underneath the contact by detecting focusing peaks. Although only the edge can be studied using this technique, actually this region is crucial for the current transport. Figure 2 shows the ratio of collector voltage and injector current V_c/I_i as a function of B at four sets of gate voltages. The temperature is 7 K, which was chosen to keep the focusing in the classical regime. The number of subbands for both QPCs is increased from one to several for the curves from (a) to (d). Focusing peaks are present in the entire B range, but we will concentrate only on the peaks at $B < 0.18$ T because in this range $r_{\text{cycl}} > 0.5$ μm. The observation of these peaks explicitly verifies the existence of a 2DEG. We briefly mention that our other measurements in the contacts by shining light or by varying B up to the quantum Hall regime also confirm this conclusion. Analysing magnetoresistance data in the low-field regime using a model described in [10], we obtained a reduced mobility of $\sim 1 \times 10^5$ cm^2 V^{-1}s^{-1} under contacts. Also, the presence of disorder is manifested by the reduced focusing peak height and is found in quantum interference measurements made at much lower temperatures. The typical peak spacing of 42 mT observed is larger than the calculated value (38 mT) based on the given n_s, which may imply a 20% increase in n_s underneath the contact.

We also studied the conductance of a QPC as a function of gate voltage at $T = 80$ mK, by varying parallel magnetic fields B from 0 to 1 T in which the contact can be switched from a superconducting state to a normal one. We observed well-defined conductance steps in units of $2e^2/h$ in three QPCs from two samples. But none of them shows an enhancement in the quantized conductance [11]. Although an enhancement has been reported previously, the result could unfortunately not be reproduced [12].

Figure 3 shows a cross-sectional HREM micrograph of a Sn/Ti contact, studied by a JEOL 4000EX/II with a Gatan on-axis parallel electron energy loss spectrometer and at 400 kV. The different layers in the heterostructure are distinguished through both their images and position-resolved electron energy loss spectroscopy. The GaAs–AlGaAs interfaces are hardly affected by the annealing, implying that a 2DEG can be preserved. This result also shows that Al $\rightleftharpoons$ Ga diffusion does not take place to a great extent. A similar result on the GaAs–AlGaAs interfaces was found in Sn/Pd contacts [14]. It is not yet clear why the GaAs–AlGaAs interfaces are not affected by the annealing. Next to the GaAs cap layer there is an amorphous layer somewhere, which is identified as an oxide layer of Ti_xO_y. This layer is discontinuous and this micrograph shows an oxide-free area. Furthermore, unlike NiAuGe ohmic contacts, the HREM observations of several contacts including the Sn/Pd never show any indication of metallurgical spikes.

No transport models have so far been developed for Sn/Ti contacts. In the literature, there have been two different models developed to explain the transport through AuGeNi contacts to a GaAs/AlGaAs interface. One is that of intermetallic spikes which are formed during annealing and which contact with the 2DEG. The existence of the spikes has been confirmed by HREM observations [13]. The other [9] describes the contacts as carrying currents from the metal to the 2DEG via highly doped

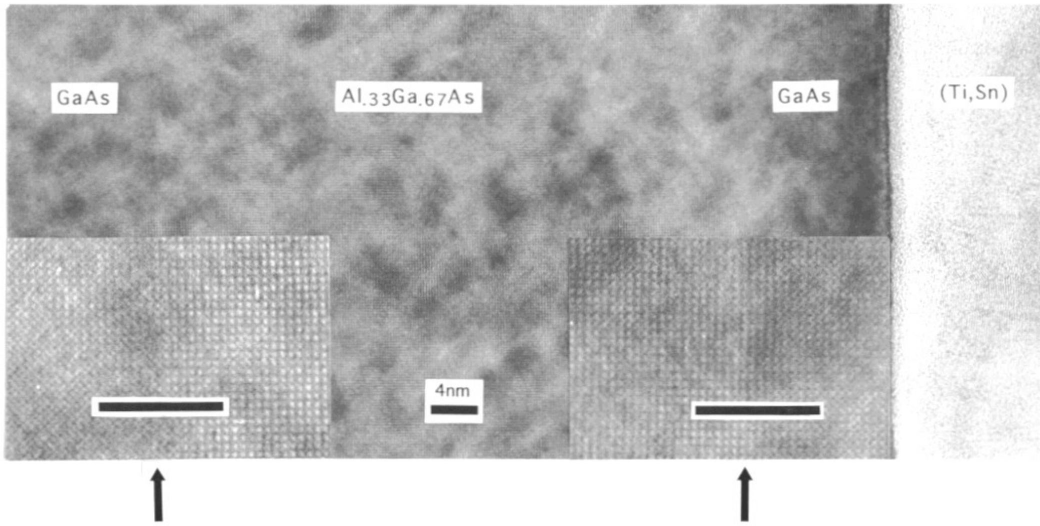

Figure 3. A cross-sectional HREM micrograph of an annealed Sn/Ti contact to a GaAs/AlGaAs heterostructure. The two GaAs–AlGaAs interfaces are indicated by arrows. The magnified cross-section of each GaAs–AlGaAs interface is given in the insets. In each inset the location of the interface is aligned to that in the micrograph. The bars in the insets are also 4 nm.

semiconductors. The contact can therefore be described by the metal–doped semiconductor interfacial resistance and the doped semiconductor–2DEG interfacial resistance. The presence of a 2DEG assumed in the model has been confirmed experimentally by using the magneto-TLM technique [9].

Based on our HREM result and regarding the difference between the materials, the Sn/Ti contacts are concluded to be non-spiking, although the possible existence of a few highly conducting spots, not being fully developed intermetallic spikes, cannot be excluded. The discovery of the 2DEG underneath the contact convincingly demonstrates that the present contacts follow the second model. Therefore, we can also conclude that the superconductor does not usually make ultimate contact with the 2DEG.

In summary, we have studied the electronic properties underneath a Sn/Ti contact in an GaAs/AlGaAs device by applying the electron focusing method and analysed the I–V characteristics of the contacts. In combination with the cross-sectional HREM observation, we conclude that the superconducting contacts formed are located above the 2DEG, which is still preserved, and that only a fraction of the S–Sm interface is transparent, although non-spiking contacts remain. Finally we point out that this electron focusing technique is also appropriate for the study of other ohmic contacts in GaAs/AlGaAs systems.

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